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An Integrated Optimum Design Approach For High Speed Prop-Rotors Including Acoustic Constraints

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Objectives

The objective of this research is to develop optimization procedures to provide design trends in high speed prop-rotors. The necessary disciplinary couplings are all considered within a closed loop multilevel decomposition optimization process. The procedures involve the consideration of blade aeroelastic, aerodynamic performance, structural, dynamic design requirements and acoustics. Further, since the design involves consideration of several different objective functions, multiobjective function formulation techniques are developed.

Accomplishments

Analysis

The aerodynamic formulation is based on the model initially developed by Smith [1] and later modified by Talbot [2]. In this model, the two dimensional aspects of rotorcraft airfoils are modeled more accurately than traditional 2-D airfoil theory. Further, analytical closed form expressions are available for the calculation of aerodynamic performance in terms of variables such as planform, camber and thickness. The procedure is easy to implement within an optimization procedure as it offers significant computations advantages from comprehensive codes. This code has been further modified by the authors for implementation within an optimization environment. The structural analysis for the rotor blade is based on a semi-analytical formulation of a highly swept anistropic box beam. This formulation extends the work first presented by Smith and Chopra [3] to include blade pretwist and sweep.

The acoustic analogy in its various forms, such as those developed by Ffowcs Williams and Hawkings and by Farassat, comprises a general theory appropriate for moving or stationary sources and moving or stationary observer. Nevertheless, suitable treatment of source motion in the acoustic analogy equation depends on the problem under consideration as well as the computational requirements and desired efficiency. Many practical acoustics problems involve a moving source and an observer moving in a related, but not identical manner. Examples of such problems include those to determine the noise heard by an observer traveling in a moving vehicle. Of particular interest here is the noise heard by a passenger in a propeller-driven aircraft.

A majority of the researchers dealing with aspects of propeller noise consider a propeller moving forward at constant velocity and with constant angular speed. The observer is generally regarded to also move forward with the propeller hub but not to rotate, though some studies have considered the case of the observer stationary with respect to the ground so that the propeller "flies over" the observation point. The latter case is not reviewed in this work, but it is easily handled using the "moving source" approach to solution of the acoustic analogy equation.

The current work envisions the physical situation described above in an alternative manner. It is completely equivalent to consider the propeller hub and the observer as stationary and to superpose a mean flow on them both. In this approach, the propeller rotates relative to fixed space, but it has no other motion. A convective wave equation describes the sound propagation in this system. Though not so straightforward as for the stationary wave equation, solution of the alternative equation follows along similar lines. The largest differences in the two solution procedures occur in the numerical implementation rather than in the analytical development.

Solution methodologies for both moving observer and moving medium have been developed, and considerations for such numerical procedures as taking a partial derivative in a moving frame have been examined. To verify the accuracy and the speed of the code, both methods have been applied to predicting the noise of a modern propeller. As shown in Figure 1, initial results indicate that the "moving medium" calculation is approximately twice as fast as that for the "moving observer." This method of calculation will be beneficial when the acoustics code is coupled with the optimizer.

Multiobjective Formulation

Due to the fact that some of the optimization problems involve more than one design objective, the objective function formulation is more complicated. In most of the existing work, the individual objective functions are combined using weight factors in a linear fashion. Such methods are judgmental as the answer depends upon the weight factors which are often hard to justify. Therefore, the problem is formulated using the Kreisselmeier-Steinhauser (K-S) function approach [3].

Multilevel Decomposition

A multilevel procedure is developed to decompose the complicated design problem, associated with large numbers of objective functions, constraints and design variables, into sub levels. Optimization is performed at each level and the levels are coupled through the use of optimal sensitivity parameters.

Optimization Implementation

A nonlinear programming method, as implemented in the numerical code CONMIN [4], is used for the optimization. CONMIN uses the method of feasible directions. In the optimization process, many evaluations of the objective function and constraints are required before convergence to an optimum design is obtained. Therefore, the process can become computationally expensive if exact analyses are performed for every function evaluation. Therefore the use of an approximate analysis is implemented in the calculations of both the objective functions and the constraints. The approximate analysis used for this study is the two point exponential procedure developed by Fadel et al. [5]

Optimization Problems

As a first step towards a fully integrated design, an integrated aerodynamic/structural optimization problem is formulated. The problem is decomposed into two levels. In the upper level, the aerodynamic optimization is performed using the hover figure of merit (FM) and the high speed cruise propulsive efficiency (η_{ax}) as the individual objective functions to be maximized. The design variables used are the blade planform, twist, thickness, camber and sweep distributions. In the second level, the structural optimization is performed and the blade weight is minimized subject to stress and deflection contraints. The design variables used in this level are the composite ply stacking sequence, the number of plies of a given orientation and the outer dimensions of the box beam. The two levels are coupled through optimal sensitivity parameters.

The aerodynamic optimization of the upper level has been completed and some representative results are presented in Figs. 2 - 6. Figure 2 shows the signifcant increase in the high speed cruise propulsive efficiency (55.9 percent) from reference to optimum. The hover figure of merit is also increased by 5.5 percent. The physical planform variables of the reference and optimum proprotors are presented in Figs. 3 - 6 where significant changes are observed for the chord, twist, zero lift angle and thickness distributions from reference to optimum. From the figures it is seen that the optimum rotor represents a compromise between cruise and hover. As indicated through the thickness to chord ratio distributions (Fig. 6) these values are significantly reduced to over come the drag divergence Mach numbers in cruise. However, such airfoils are associated with lower C_{Lmax}. Therefore, the solidity must increase in order for the optimum rotor to maintain the same lifting capability in hover as the reference rotor. The increase in blade solidity is

demonstrated through the increase in the optimum chord, at both inboard and outboard, in Fig. 3. The improved performance of the optimum rotor is also achieved through a more optimal twist distribtion (Fig. 4) and a more optimal zero lift angle of attack distribution (Fig. 5).

Future Plans

Research plans that are either already under progress or are soon to be implemented are as follows.

- Complete the composite box beam analysis with pretwist and sweep and incorporate it into the second level optimization. Perform the integrated aerodynamic/structural optimization.
- Evaluate the acoustical performance of the rotor designed for an aerodynamic and structural point of view using the acoustic code currently being developed.
- Integrate acoustics into the optimization design process for a full multidisciplinary optimization design problem.

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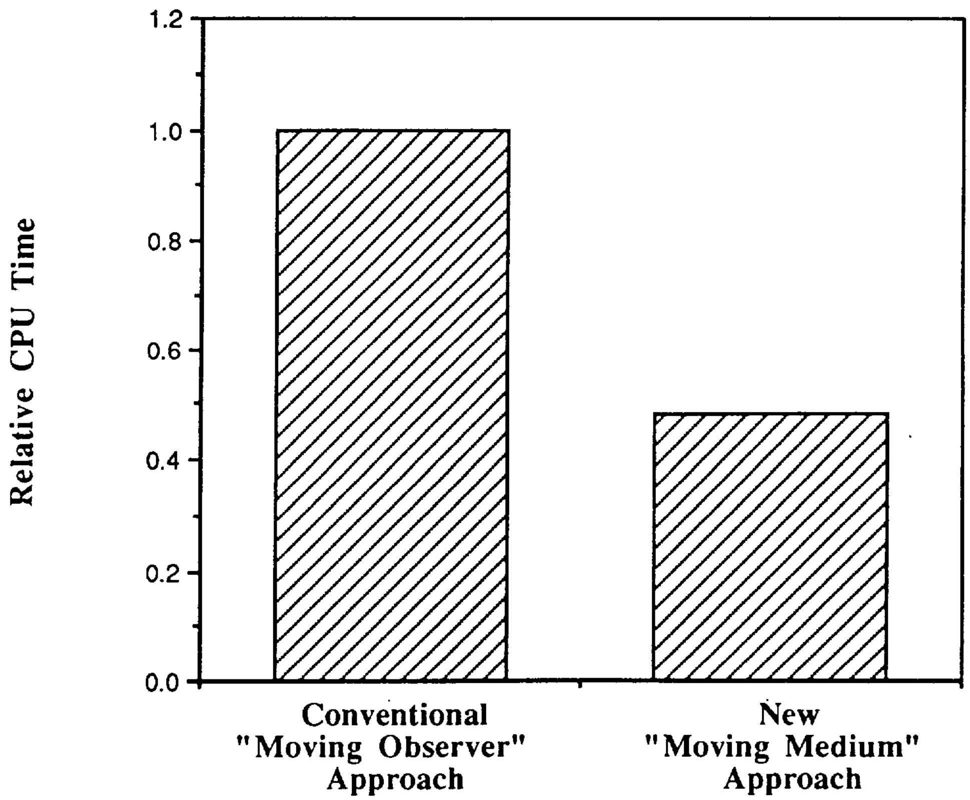

Figure 1. The Relative CPU Time Required for the two Methods.

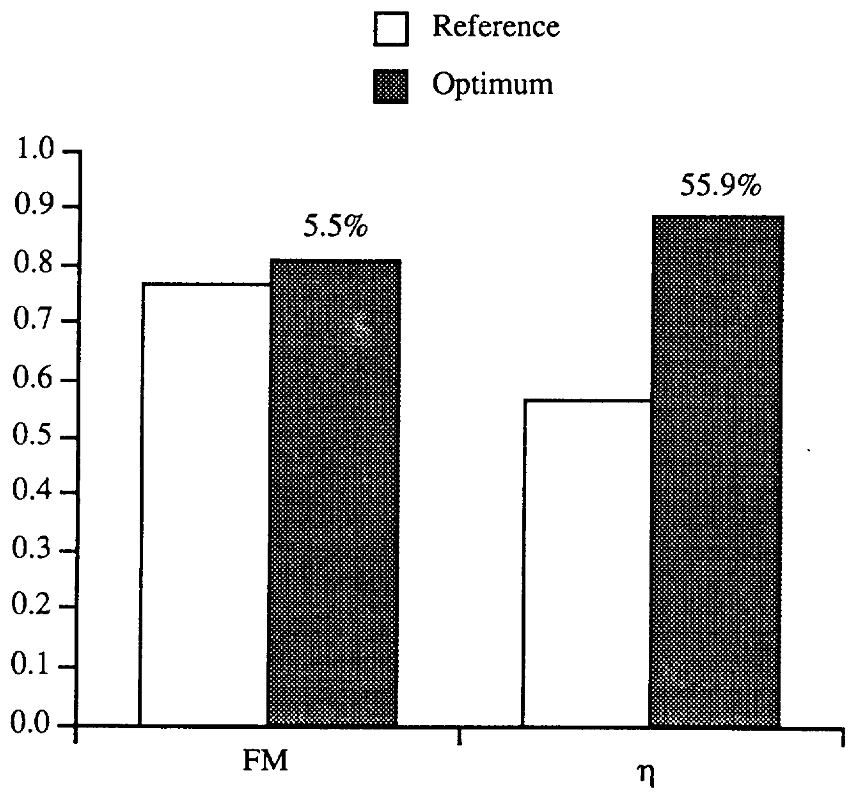

Figure 2 Comparison of optimum results

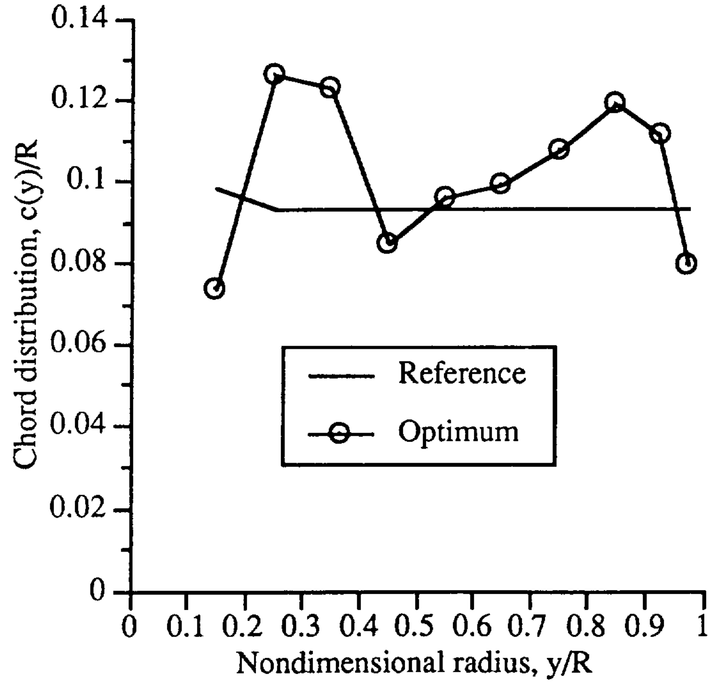

Figure 3 Blade chord distribution

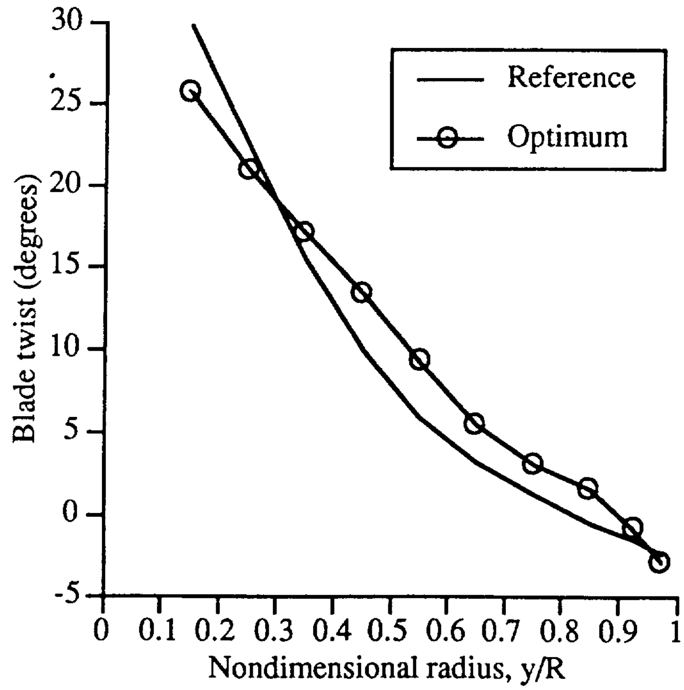

Figure 4 Blade twist distribution

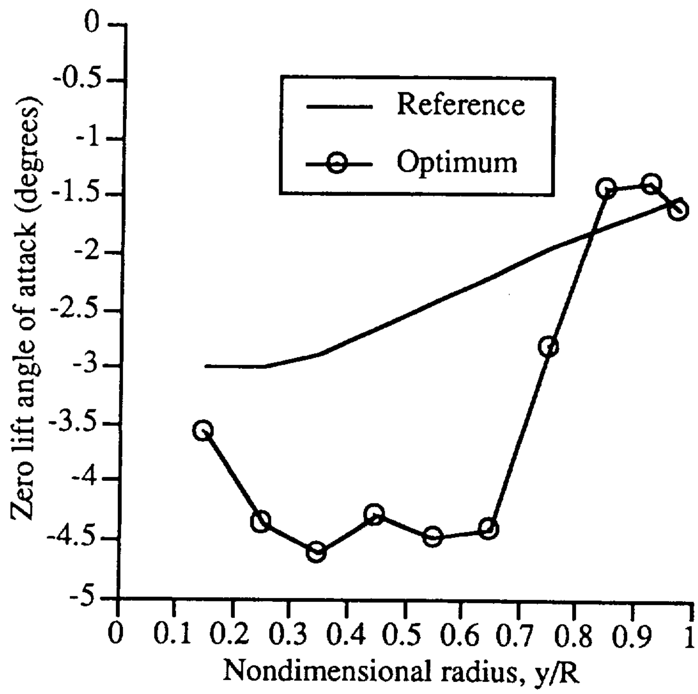

Figure 5 Blade zero lift angle of attack distribution

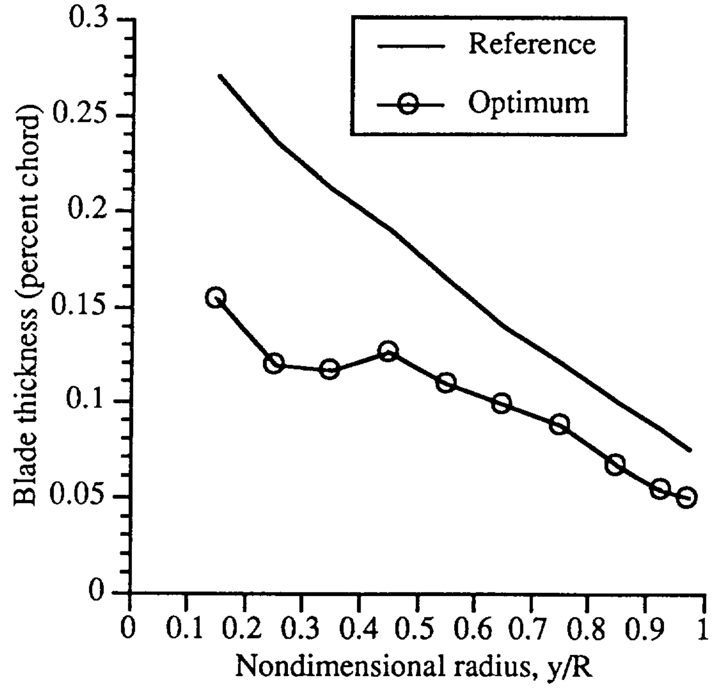

Figure 6 Blade thickness distribution